Proof of concept for underwater localization, characterization, and excavation of partially-buried munitions using robotic perception and control

MR24-4529

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In-Progress Review Meeting

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Project Team

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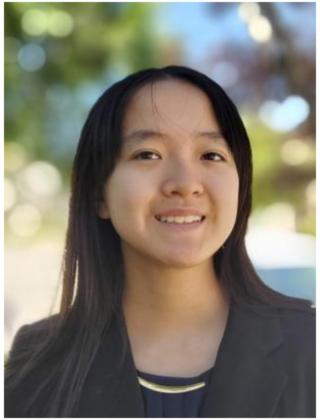

Amy Phung
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Bottom Line Up Front

What is being evaluated:

Underwater localization, characterization, and precise excavation of partially buried objects in low visibility conditions using a robotic arm operating the SHARC (SHared Autonomy for Remote Collaboration) framework

What is going well:

Real-time opti-acoustic data fusion for scene reconstruction, automated excavation

What is not working:

Nothing to report

What support is needed:

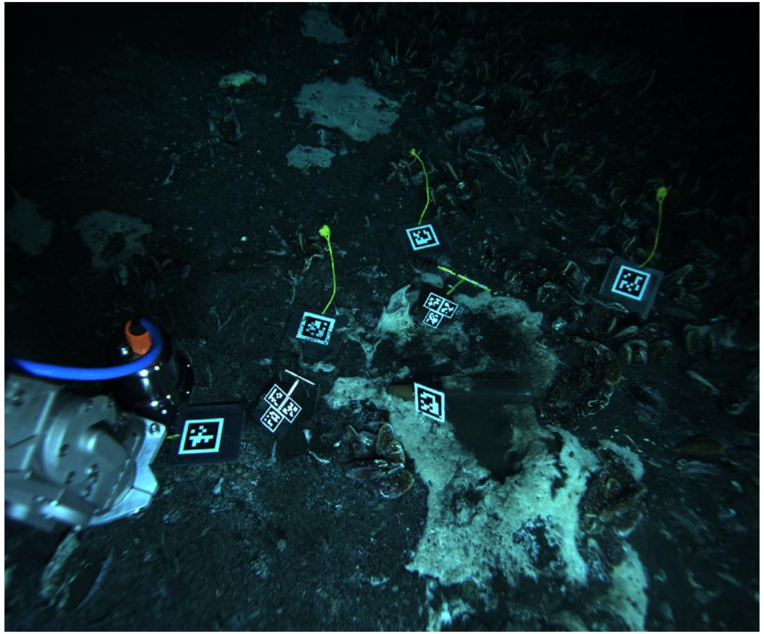
Program objectives are successfully completed. Need to transition toward operational deployment.

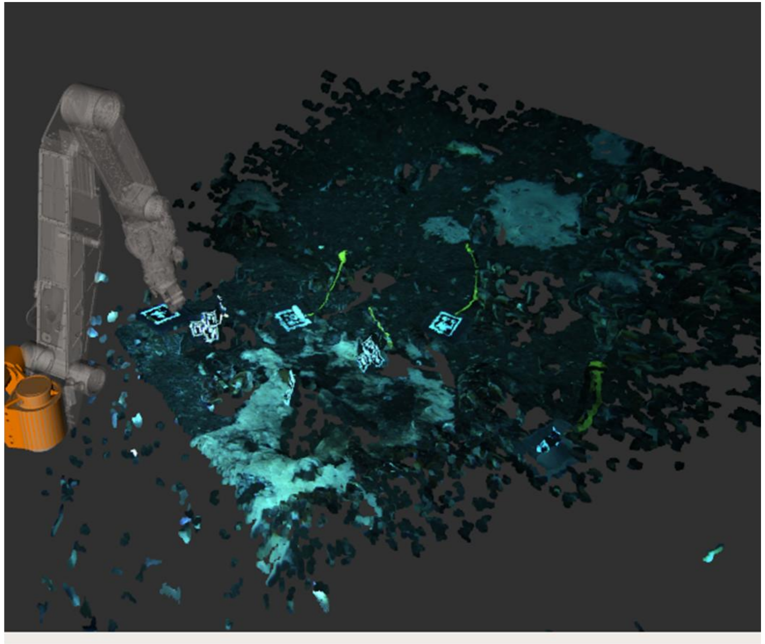
Technical Objective

1. Modify SHARC to incorporate ultra-high frequency sonar data while using jetting tool for excavation.
2. Develop a real-time process fusing optical imagery and sonar returns to generate 3D visualization of the workspace
3. Conduct tank tests to evaluate the utility of the method for localization, characterization, and excavation of partially-buried inert munitions in optically turbid water using a robotic arm.

Technical Objective: automated 3D workspace reconstruction in turbid underwater conditions

Good Visibility
NTU << 1

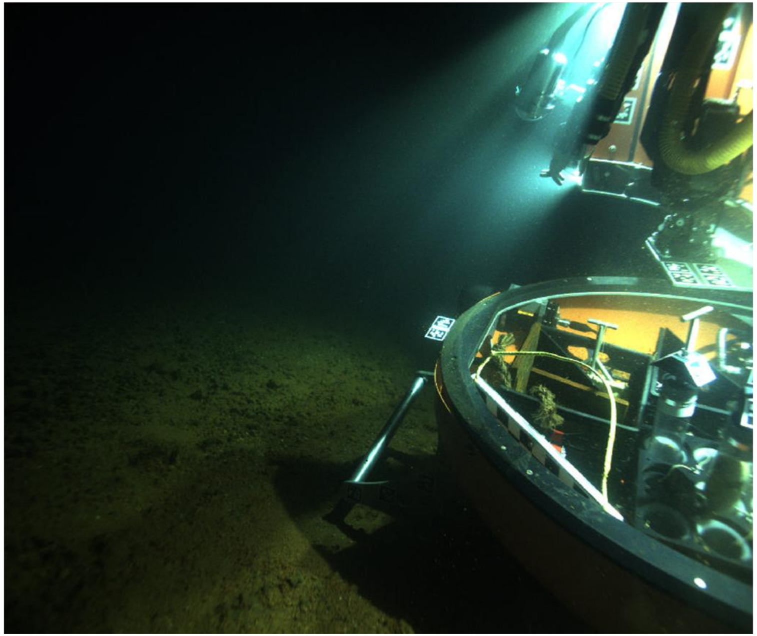


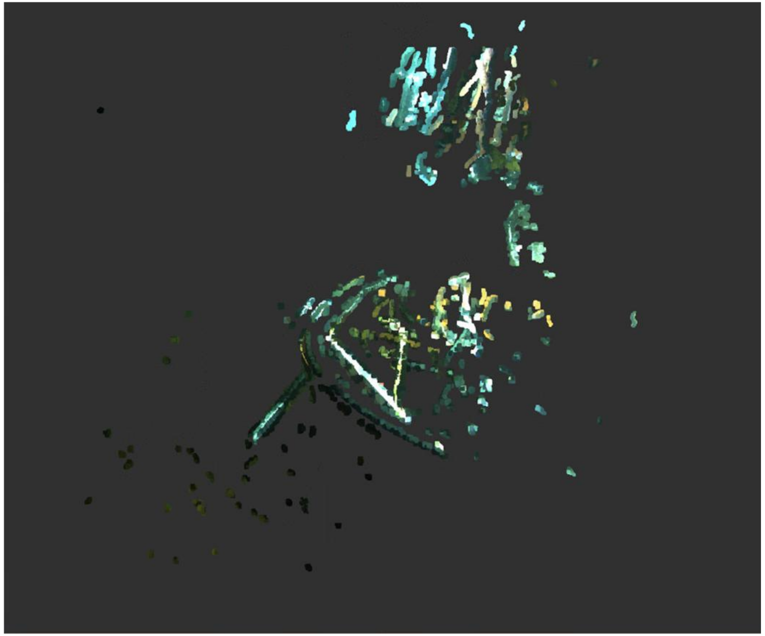


from: Billings et al. 2022

Technical Objective: automated 3D workspace reconstruction in turbid underwater conditions

Poor Visibility NTU ≥1

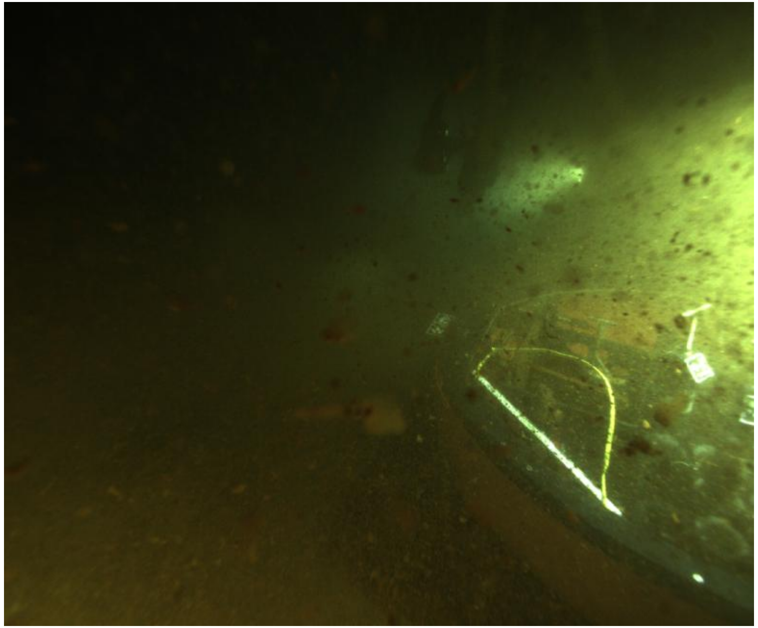




from: Billings et al. 2022

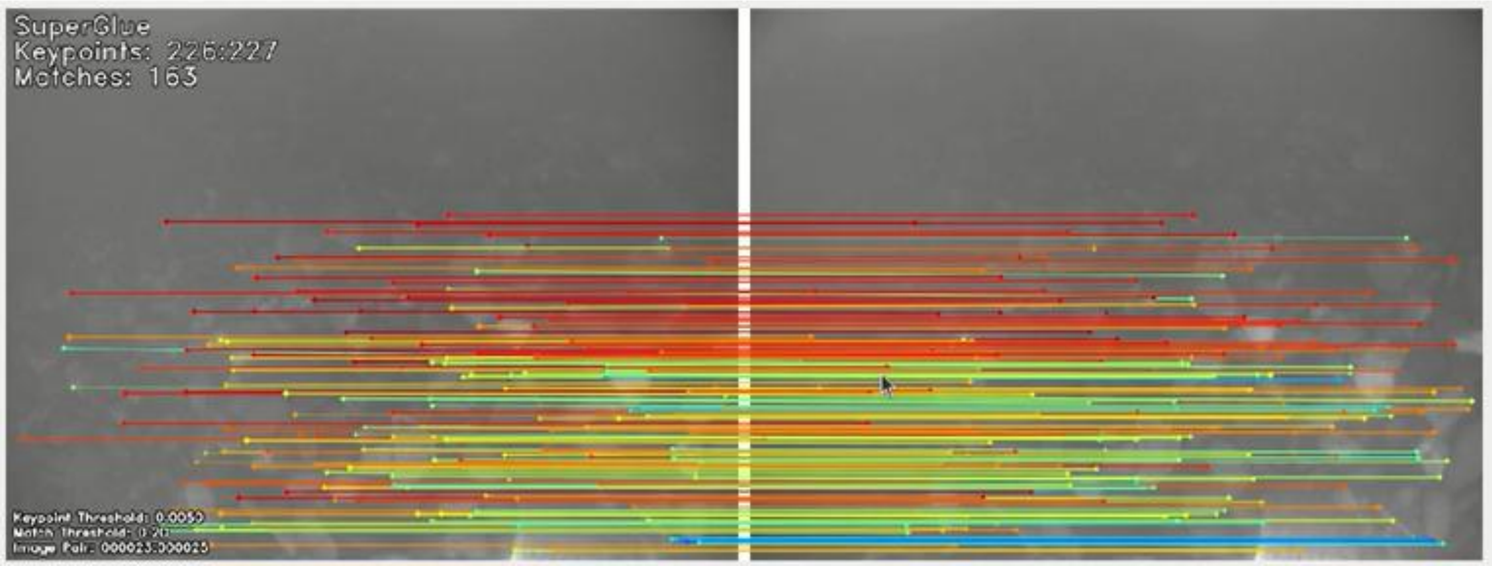
Technical Objective: automated 3D workspace reconstruction in turbid underwater conditions

Severely Limited Visibility NTU ≥6



Technical Objective: automated 3D workspace reconstruction in turbid underwater conditions

Overcome limitations of conventional state-of-the-art underwater optical 3D reconstruction (e.g., Sarlin, Paul-Edouard, et al. 2020)



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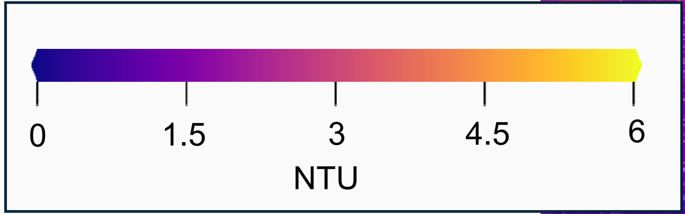
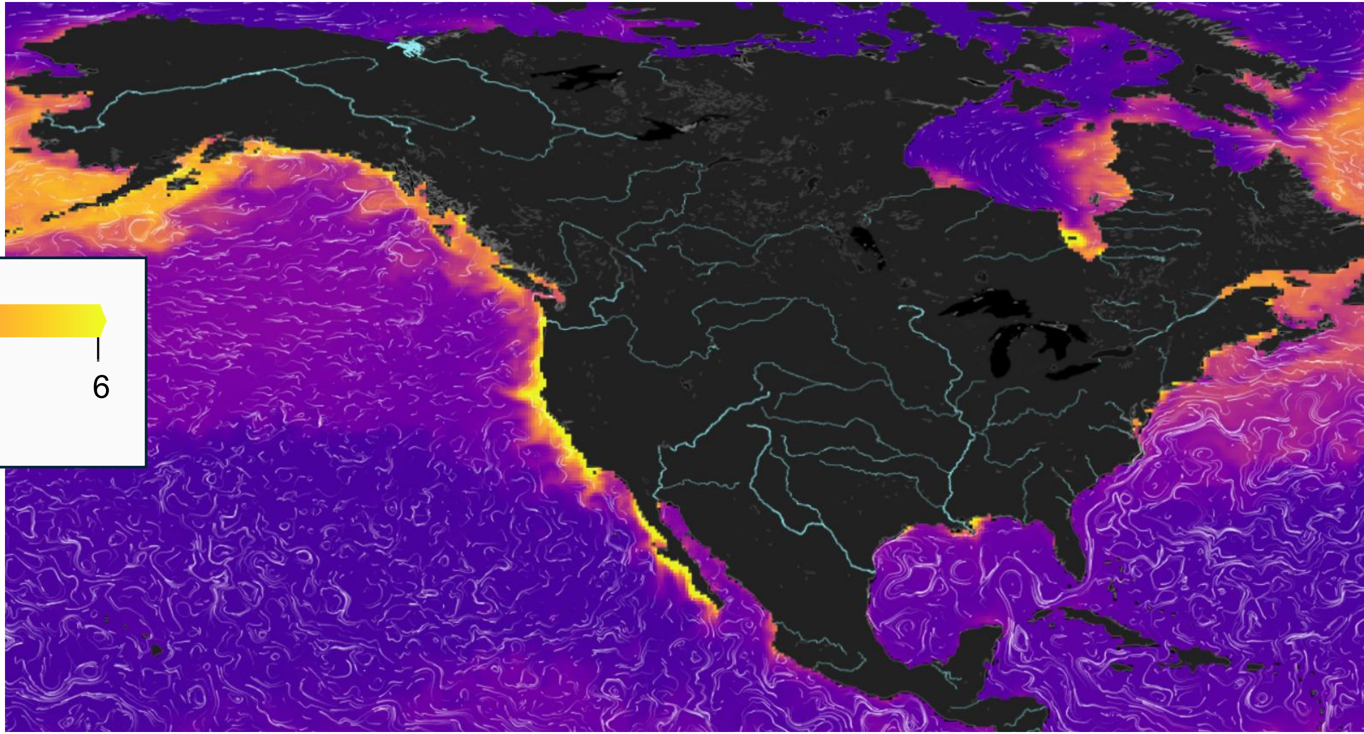
Technical Objective: automated 3D workspace reconstruction in turbid underwater conditions

Turbid coastal regions constrain 3D optical reconstruction.





Copernicus Marine Service

Data adapted from Copernicus MyOcean Viewer volume attenuation coefficient of downwelling radiative flux in sea water

Technical Objective: automated 3D workspace reconstruction in turbid underwater conditions

Overcome sonar resolution limitations caused by elevation angle ambiguity

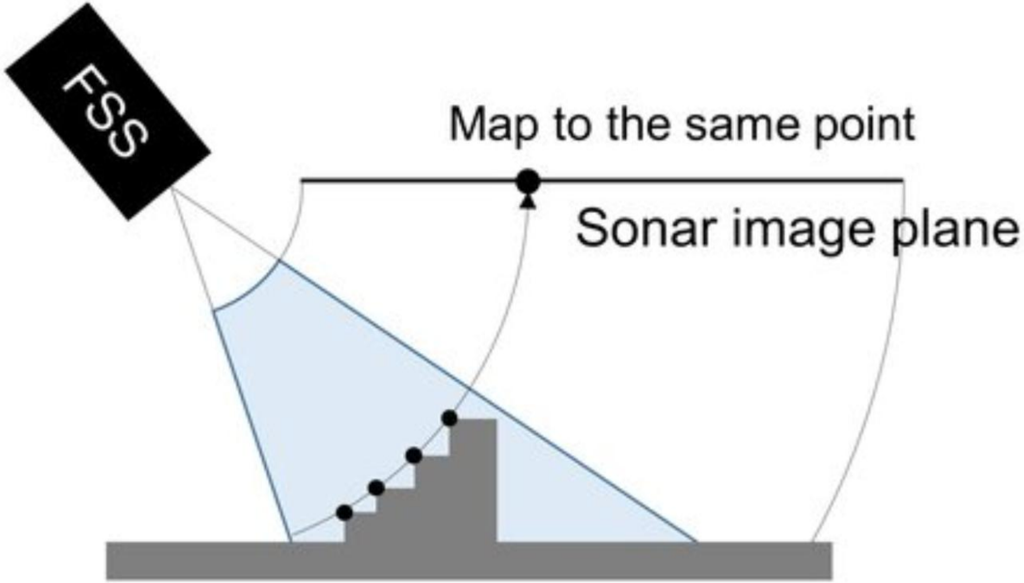


Image from: Sung, Minsung, et al. "Underwater-sonar-image-based 3D point cloud reconstruction for high data utilization and object classification using a neural network." *Electronics* 9.11 (2020): 1763.

Technical Objective: real-time data fusion

Fuse complimentary sensing modalities (optical and acoustic imaging data with manipulator pose estimates) to generate a unified 3D representation of the workspace.

Technical Approach

Task 1 ☑
Build robotic intervention testbed

- **Task 1.1 ☑** Integrate 3D optical imaging system
- **Task 1.2 ☑** Fabricate robotic arm base & pedestal
- **Task 1.3 ☑** Integrate high-Frequency sonar
- **Task 1.4 ☑** Fabricate robotic jetting tool

Task 2.1 ☑
Develop real-time 3D workspace reconstruction using fused opti-acoustic data

Task 2.2
Integrate and test jetting tool

Task 3
Go/ NoGo decision

Go

Task 4
Demonstrate proof-of-concept operation

NoGo

End program

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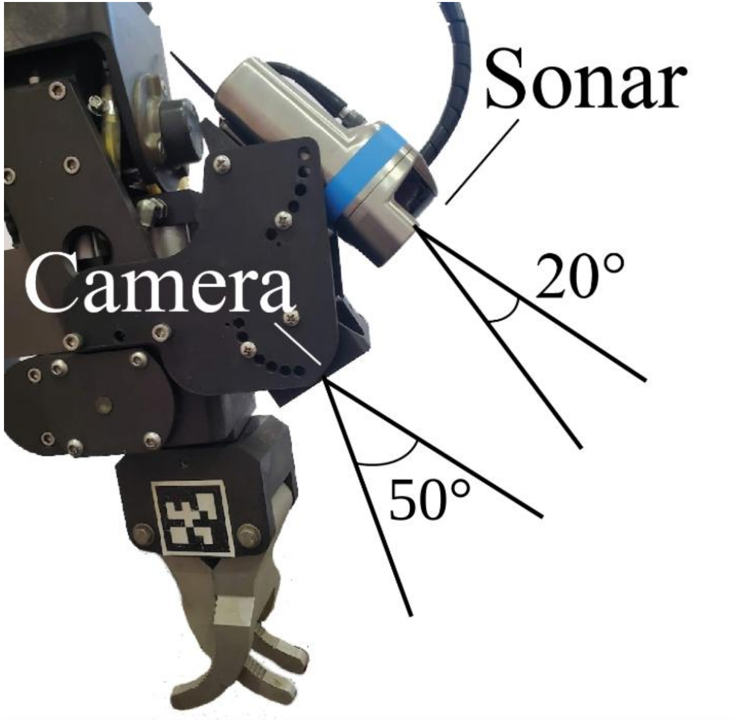
Results: co-registered optical and acoustic imagery

Stereo camera and imaging sonar placement on manipulator wrist enables co-registered optical and acoustic observation.



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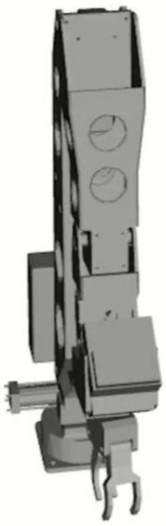
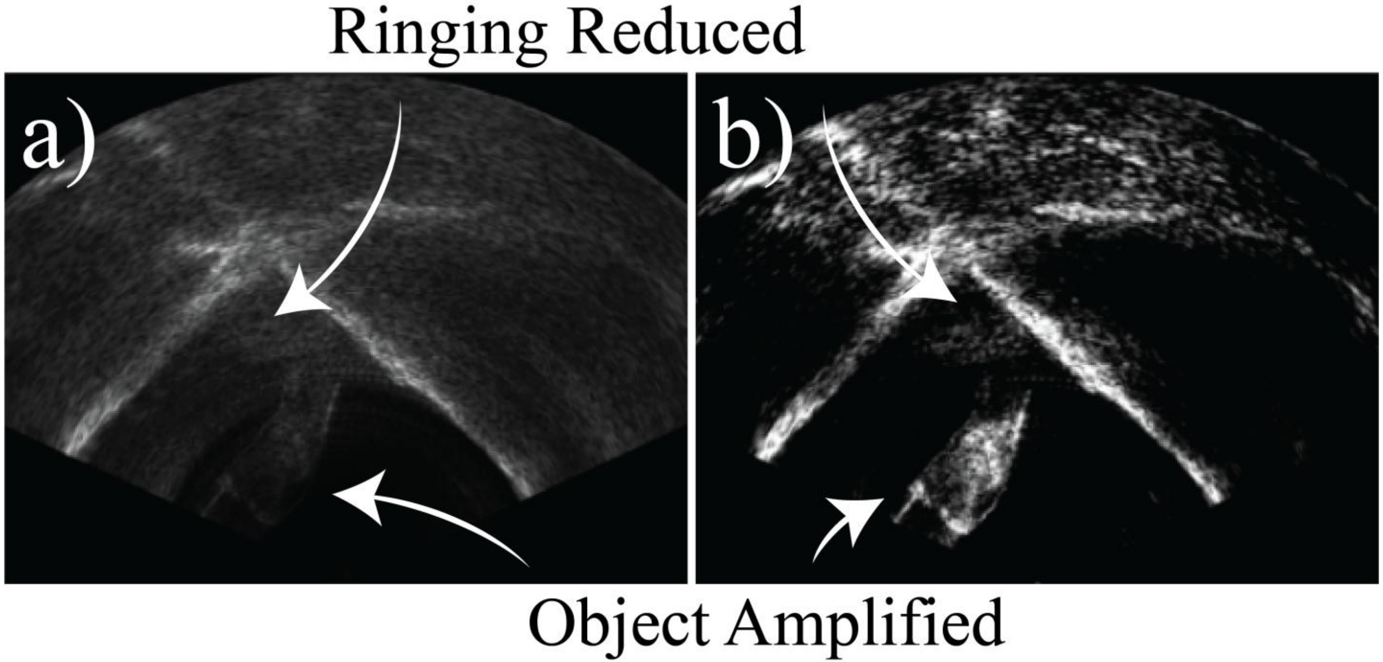
Results: acoustic reconnaissance from a safe position

Initial acoustic scan of workspace from a safe location using orthogonally swept trajectory to minimize elevation angle ambiguity



Results: real-time processing of sonar acoustic data

Real-time processing of raw sonar data (a) to minimize acoustic artifact and amplify signal (b).



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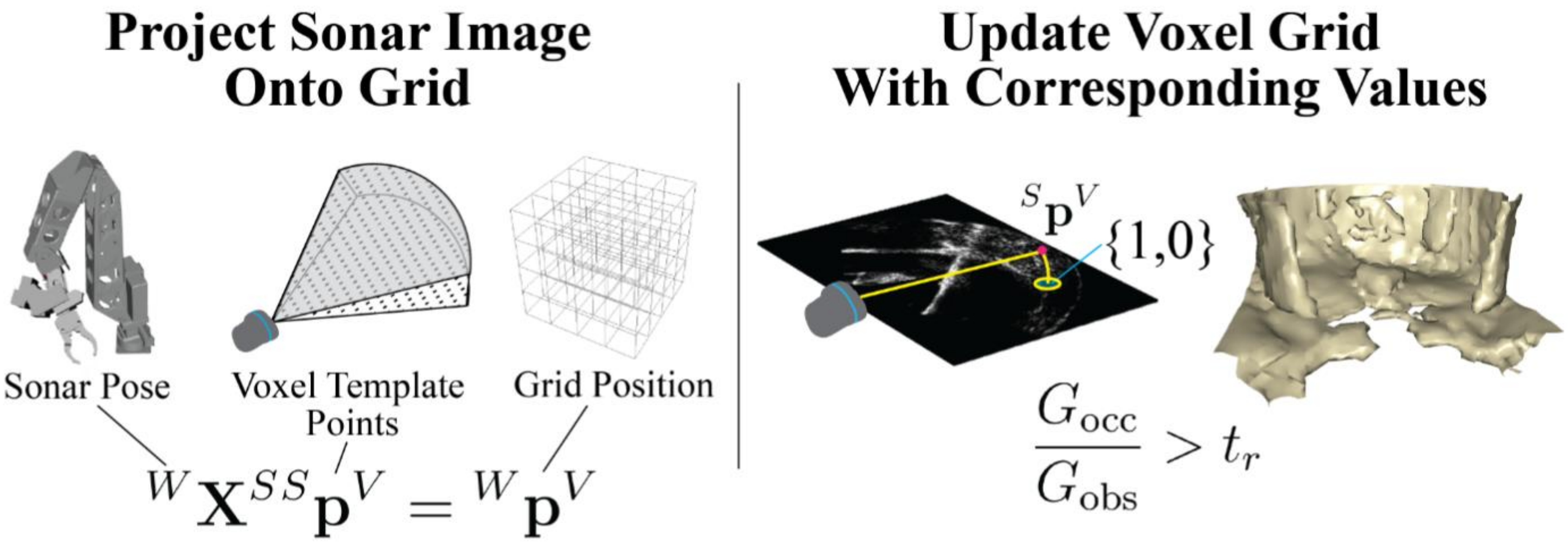
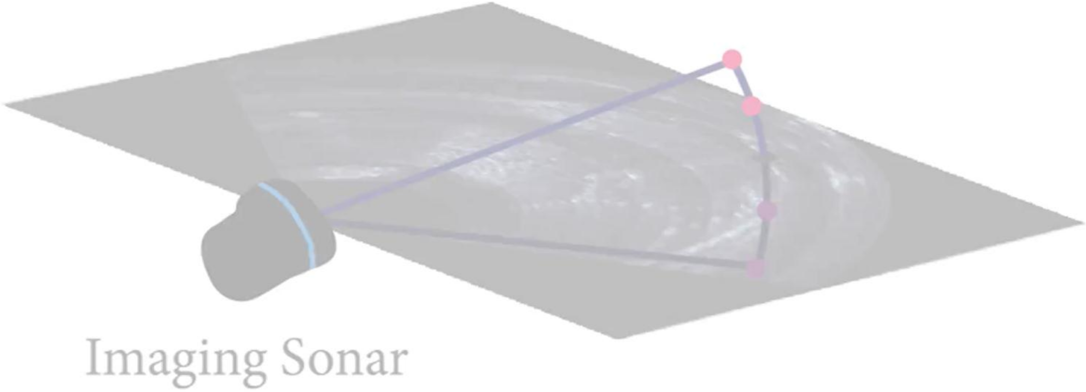
Results: 3D workspace reconstruction using sonar imagery and joint angle feedback



Results: 3D workspace reconstruction using sonar imagery and joint angle feedback



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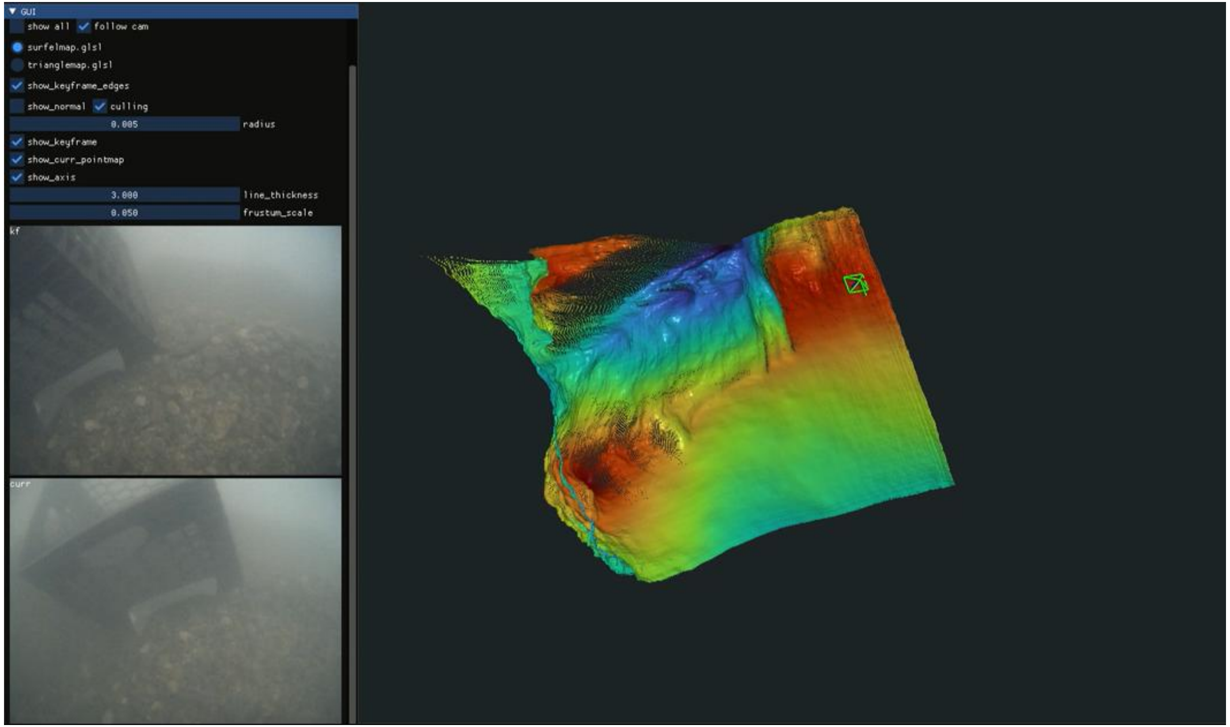
Results: real-time 3D optical reconstruction with uncertainty estimates

Real-time estimation of uncertainty in near-field 3D optical reconstruction. Cool colors indicate high confidence, warm colors indicate low confidence.



Process based on: Leroy, V., Y. Cabon and J. Revaud. 2024.

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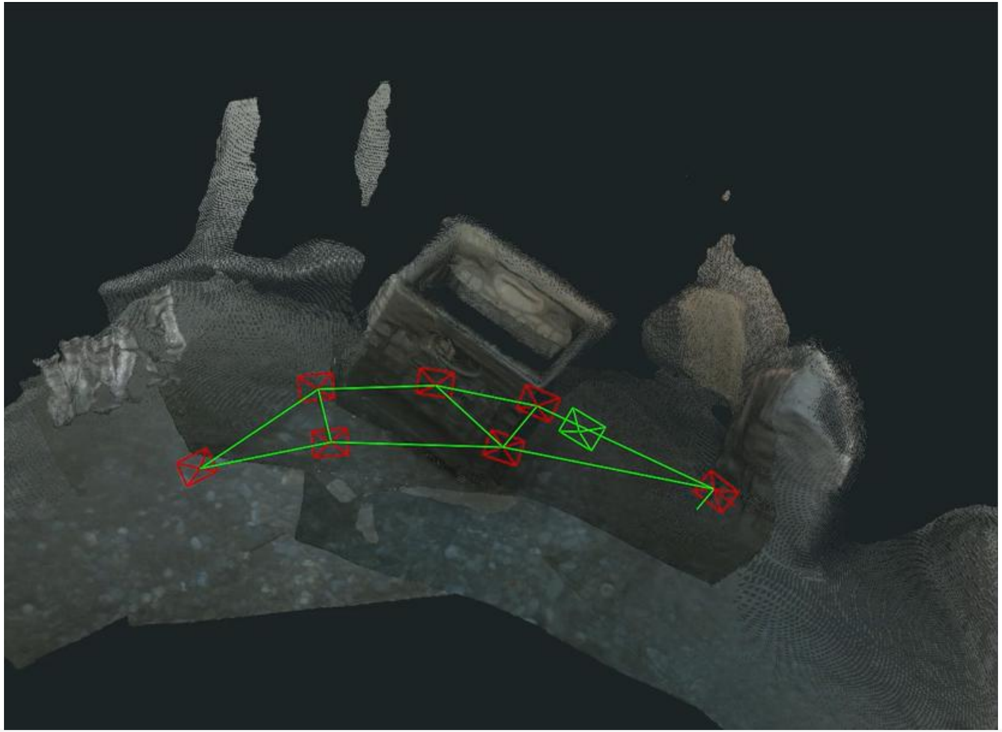
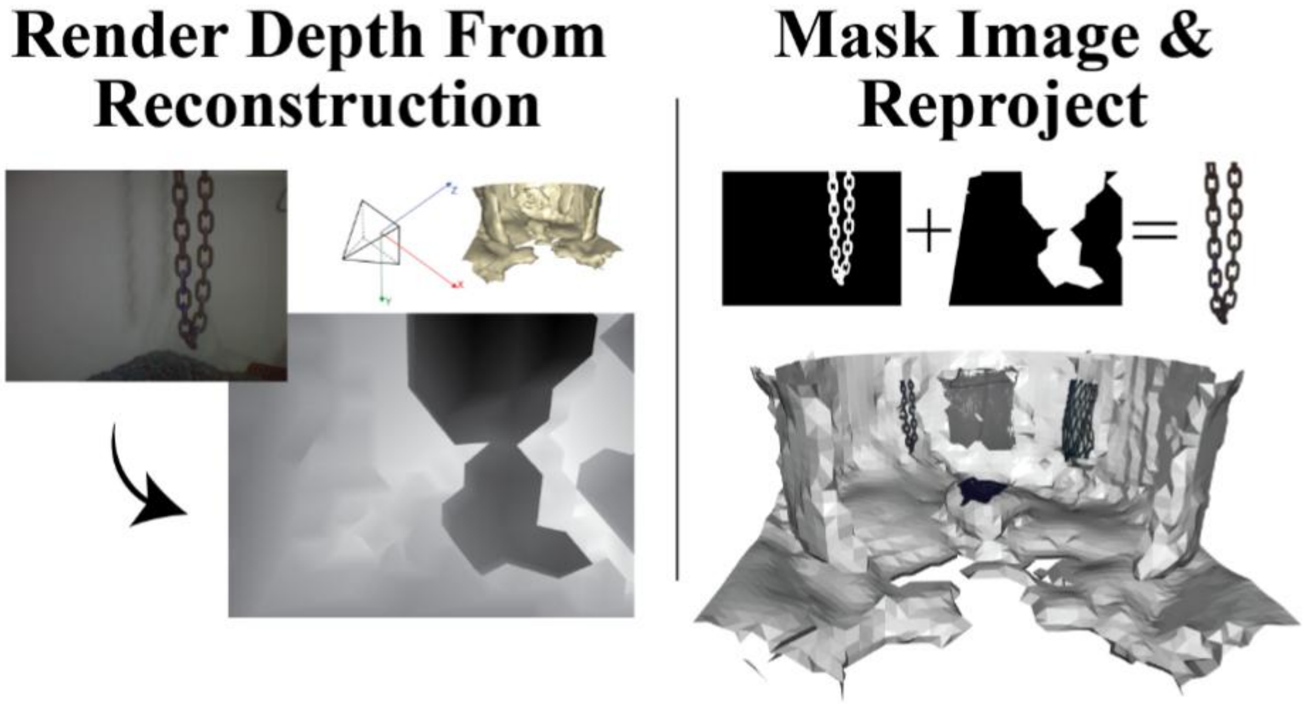
Results: 3D optical model of workspace

3D optical model of workspace using dense reconstruction with uncertainty threshold.



Results: fusion of optical imagery with acoustic reconstruction



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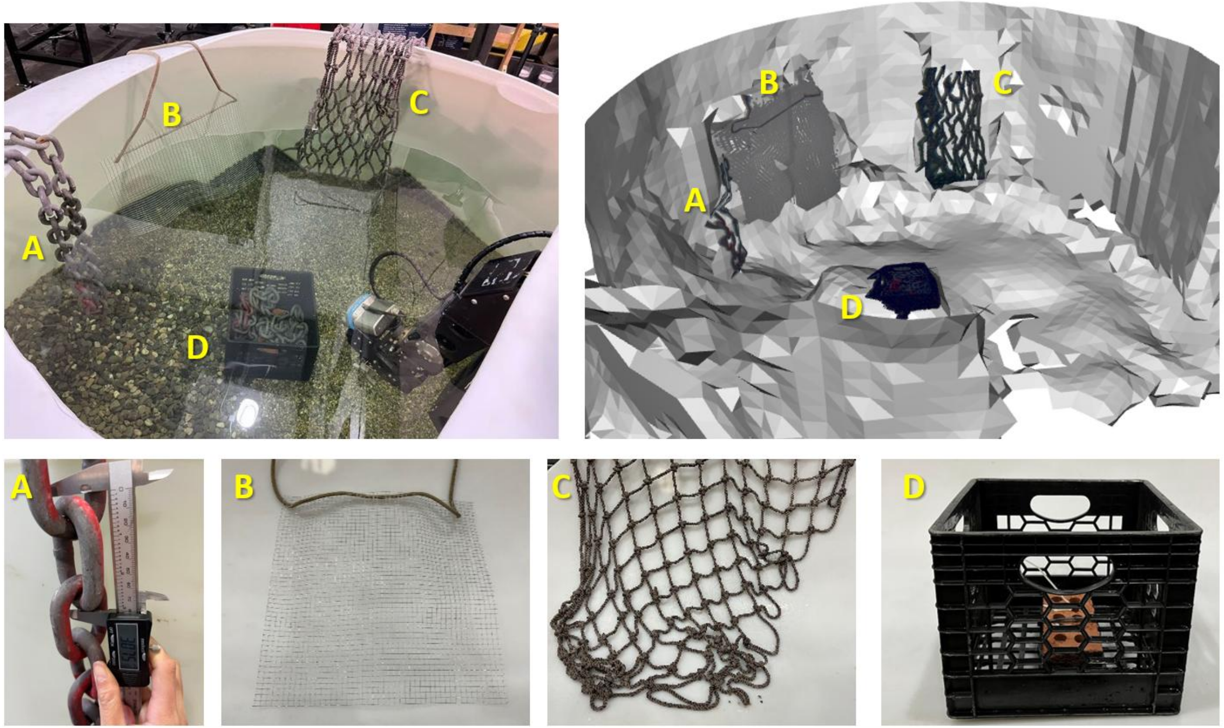
Results: example of real-time 3D workspace reconstruction process

A. anchor chain

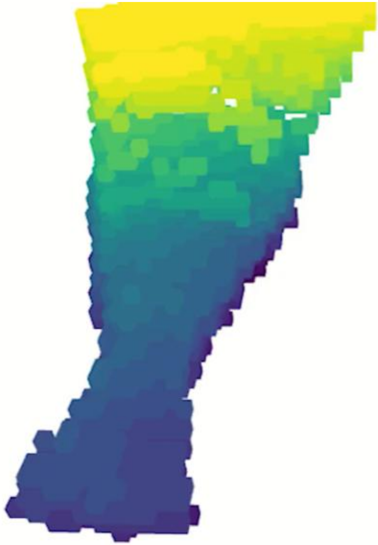
B. wire mesh

C. cargo net

D. milk crate



Results: example of real-time 3D workspace reconstruction process



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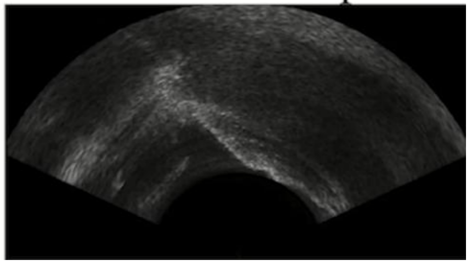
Sonar Data Input



Results: 3D reconstruction figures of merit

Processing times and equivalent framerates per sonar frame based on voxel size

Voxel Size (m)	Time Per Frame (s)	Framerate (FPS)
0.05	0.052	18.6
0.04	0.116	8.6
0.03	0.195	5.1
0.02	0.501	3.4
0.01	3.516	0.28

Optical and acoustic reconstruction accuracy, in centimeters

Object	Ground Truth	Acoustic		Optical	
		Result	Error	Result	Error
Tank	220.5 (0.4)	215.3 (1.0)	5.2	-	-
Milk Crate	32.9 (0.1)	26.3 (0.9)	6.6	22.3 (1.4)	10.6
Mesh (full width)	58.5 (2.1)	53.4 (0.2)	5.1	-	-
Mesh (10 cells)	12.7 (0.1)	-	-	11.5 (0.6)	1.2
Chain	42.0 (0.2)	-	-	33 (0.6)	9.0

*Measurement variance (due to object deformation) indicated in parentheses.

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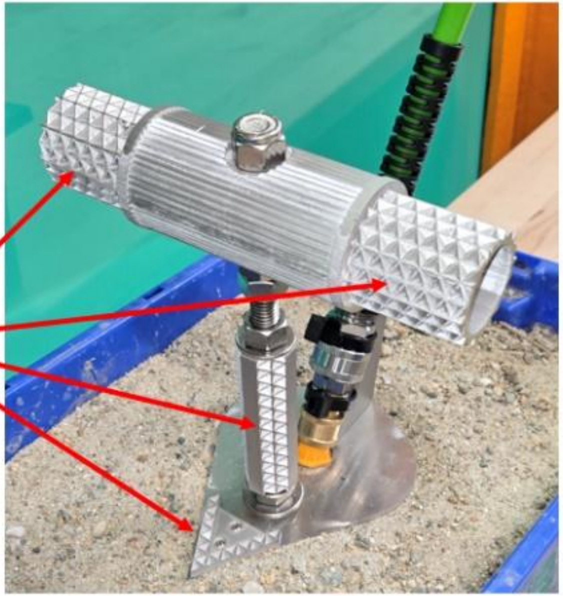
Results: performance benchmark

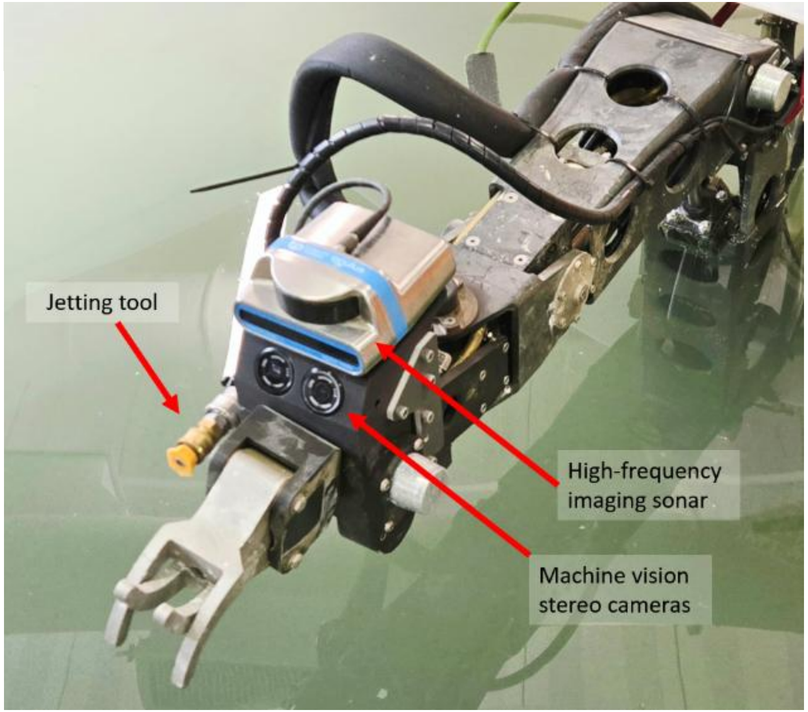
Method	Optimization Time	Rendering Time	Incremental?	Input Sensors
COLMAP	>1 Hr	Real-Time	N	Optical
AoNeuS	30 min	Minutes	N	Optical & Acoustic
3DGS	30 min	Real-Time	Y*	Optical
RTG-SLAM	Real-time	Real-Time	Y	Optical & Depth
OASIS	Real-time (18 Hz)	Real-Time	Y	Optical & Acoustic

*Possible in certain implementations

Results: automated excavation

frequency-tuned acoustic fiducial reflecting surfaces

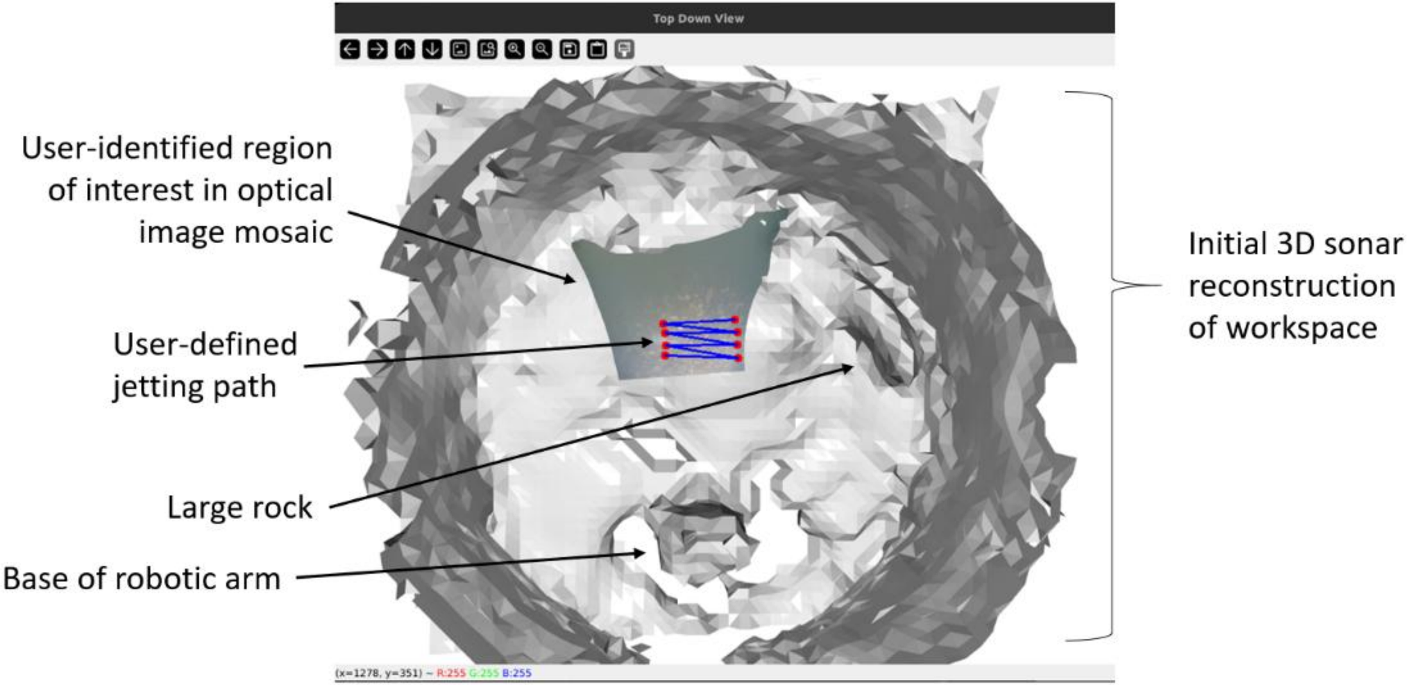




Results: excavation test conditions

Left, photo of test tank. Middle, image from wrist-mounted camera of partially buried pipe at standoff distance of 1m. Right, image of the same pipe at a standoff distance of 0.2 m. All photos taken prior to jetting, with 9 NTU water turbidity.

Results: automated excavation path planner



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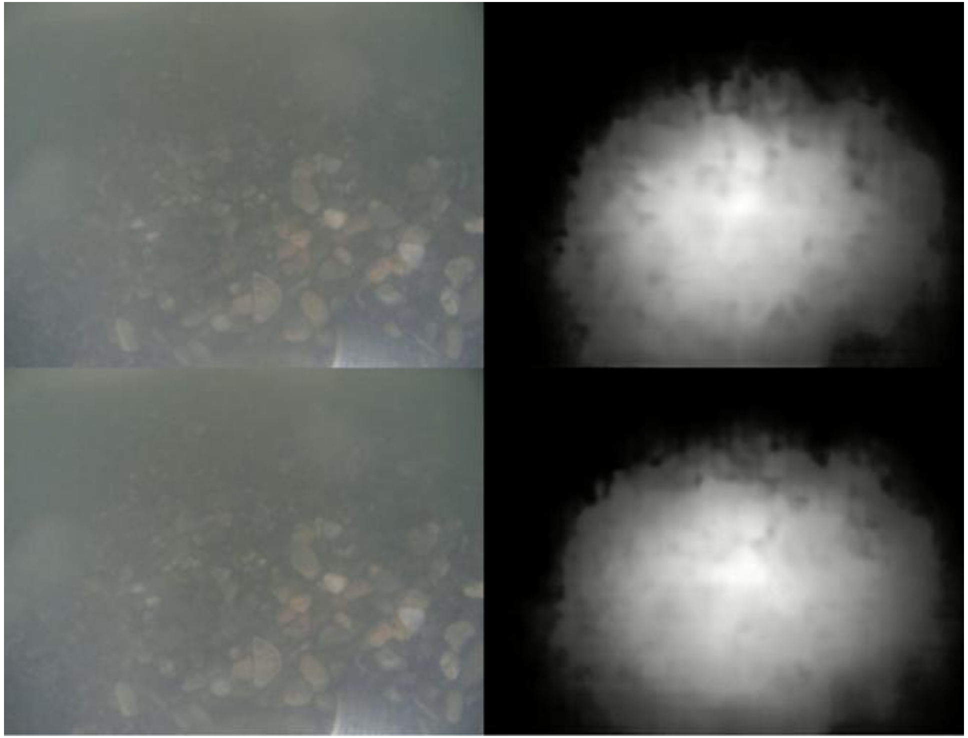
Results: optical imaging during excavation

Stereo-optical imagery recorded at 20 cm standoff distance during jet excavation process, with turbidity increasing from 9 to 14 NTU. Dense-feature confidence thresholding of optical imagery at right.



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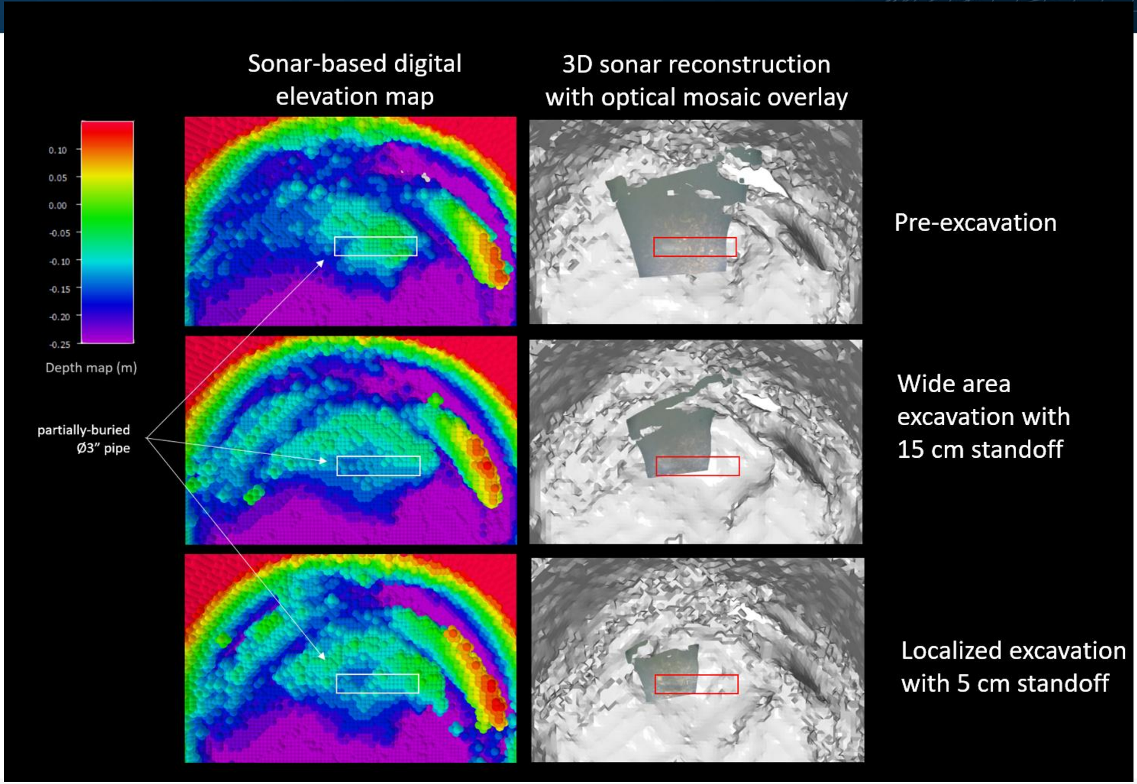
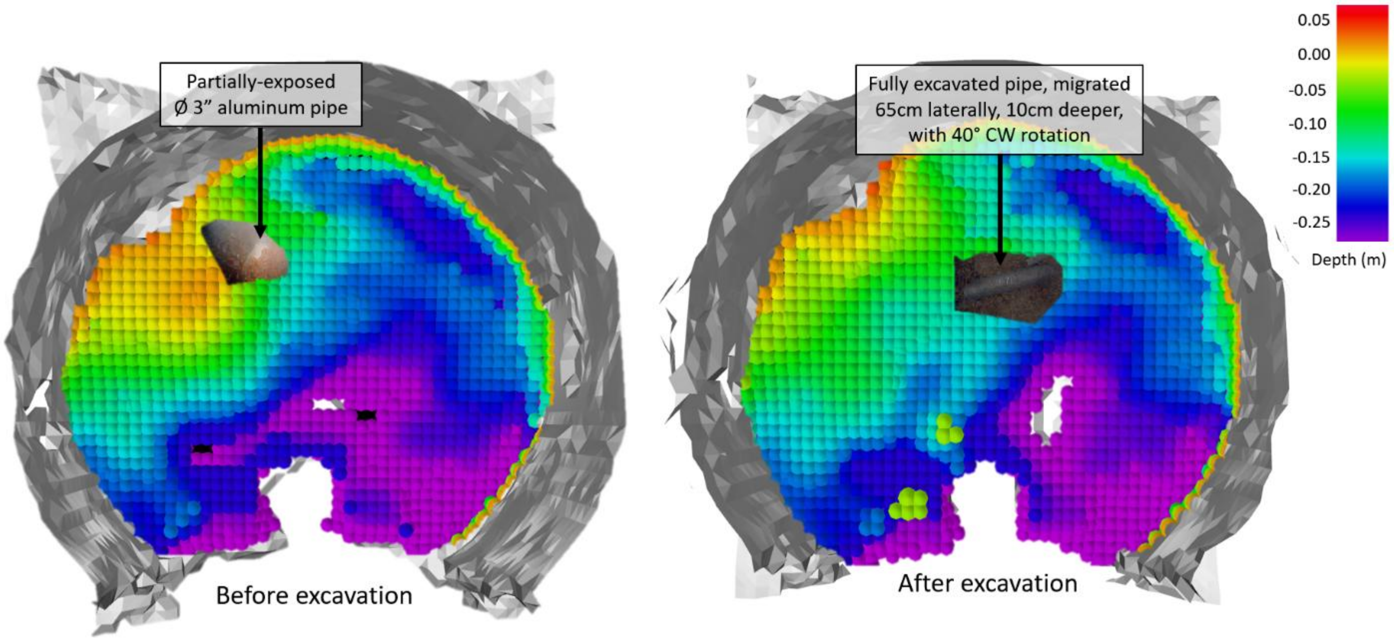
Results: automated excavation

Iterative 3D reconstruction of workspace during jetting operations.



Results: automated excavation

Buried pipe migration during excavation. Colors indicate relative depth of workspace bottom (in meters), with warm colors corresponding to shallower regions, and cool colors deeper.



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Results: automated excavation

Overhead photo of fully excavated aluminum pipe, along with a partially excavated tool handle.

- Burial depth up to 10cm within cm-scale gravel
- Excavation time <5 min
- Photographed after water column particulates fully settled.

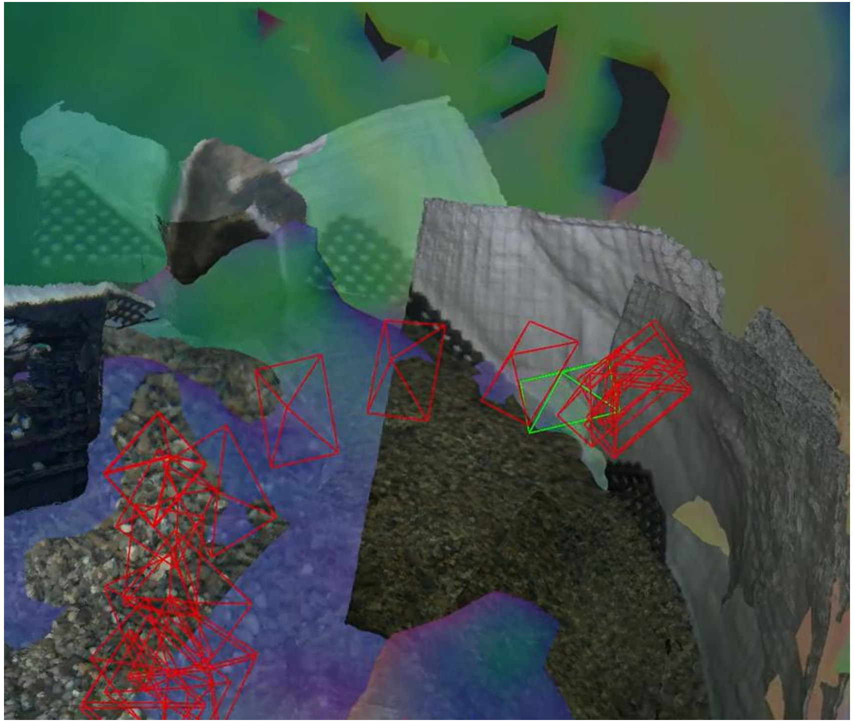
Future Research

Adaptive refinement/updating of subregions within 3D reconstruction, enabling:

- Vehicle motion compensation

- “Next best” viewpoint for enhanced scene understanding

- Differentiation of static and dynamic features within workspace



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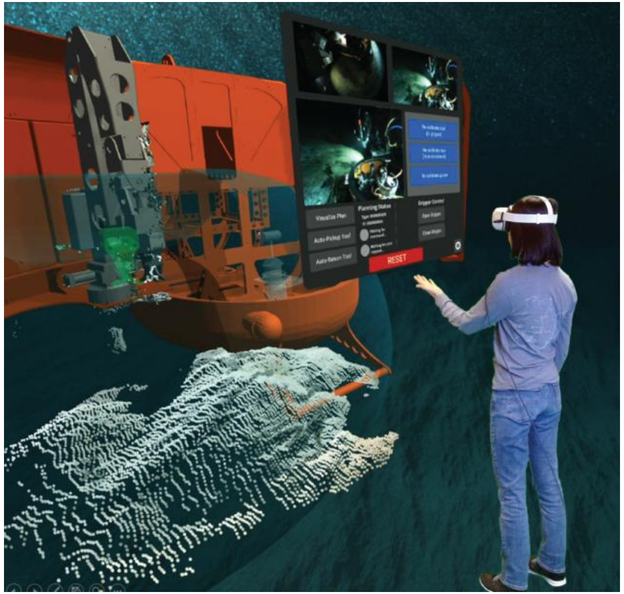
BACKUP MATERIAL

24-4529: Proof of concept for underwater localization, characterization, and excavation of partially-buried munitions using robotic perception and control

Technology Focus

- Develop a robotic process that can be used by remote operators to quickly detect, localize, classify and remediate proud and partially buried underwater munitions in low-visibility.



Research Objectives

- Fuse optical imagery with sonar acoustic data to enable real-time 3D situational awareness of workspace in varying lighting and turbidity conditions.
- Criteria for success: proof-of-concept demonstration, wherein remote operators collaboratively locate, excavate, and map in 3D a partially buried inert munition in water with visibility of less than 1m.

Project Progress and Results

- *All proposed objectives are now completed. The technology has demonstrated robotic excavation of partially buried underwater objects with visibility <0.5 m.*

Technology Transition

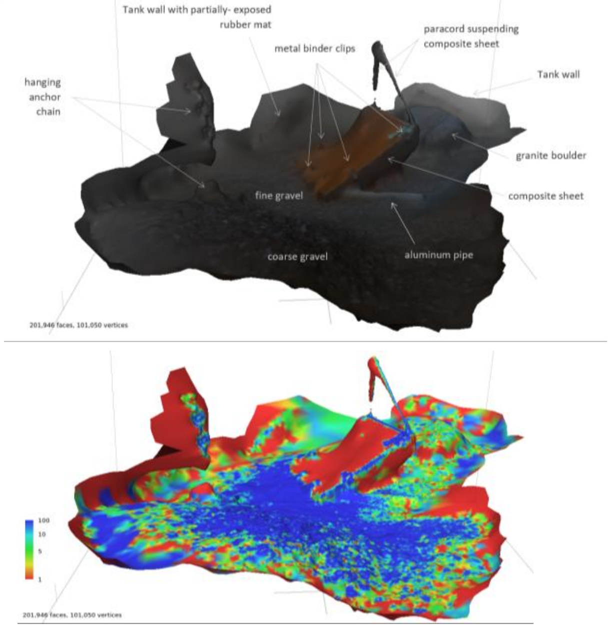
- The technology is transferrable for other DoD domains, including for mine countermeasures, NSW, and coastal infrastructure construction/maintenance. The technology may also be transferrable for use in civilian infrastructure construction/maintenance, and scientific research. A project is underway with the US National Deep Submergence Facility to conduct engineering trials using the ROV Jason.

Plain Language Summary

- Remediation of underwater munitions is slow, costly, and potentially dangerous. Conventional approaches require on-site EOD teams using teleoperated robots and rely on 2D video camera feeds for situational awareness, which is inadequate for working in turbid environments.
- This technology fuses optical imagery with sonar acoustic data to generate a real-time 3D reconstruction of the workspace. This maximizes situational awareness, enabling safe and efficient excavation and remediation operations using a robotic arm (with wrist-mounted sonar, stereo optical cameras, and water jet tool), regardless of water column visibility. The 3D reconstruction can be viewed by EOD team members located anywhere in the world using just a standard internet connection. This enables collaborative operation and guidance from off-site experts.

Impact to DoD Mission

- **Impact:** Developed a fused optical-sonar process for maintaining 3D underwater situational awareness of worksite.
- **Importance:** Can enable robotic remediation of munitions in low visibility conditions.
- **DoD advancement:** Intended to increase the efficiency and safety of munitions cleanup operations in coastal regions while lowering remediation costs.



Upper panel, fused 3D reconstruction of workspace using optical and sonar acoustic data; Lower panel confidence map (expressed in percent, where blue is high confidence, red is low confidence)

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Publications

- A. Phung and R. Camilli, "OASIS: Real-Time Opti-Acoustic Sensing for Intervention Systems in Unstructured Environments”, accepted to the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2025.
- A. Phung, G. Billings and R. Camilli, "Sonar-Aided Manipulation in Low-Visibility Conditions by Novice Users," *OCEANS 2024 - Halifax*, Halifax, NS, Canada, 2024, pp. 1-7, doi: 10.1109/OCEANS55160.2024.10753694.
- A. Phung, G. Billings, A. F. Daniele, M. R. Walter and R. Camilli, "A Shared Autonomy System for Precise and Efficient Remote Underwater Manipulation," in *IEEE Transactions on Robotics*, vol. 40, pp. 4147-4159, 2024, doi: 10.1109/TRO.2024.3431830.

Literature Cited

- G. Billings, M. Walter, O. Pizarro, M. Johnson-Roberson, and R. Camilli. “Towards Automated Sample Collection and Return in Extreme Underwater Environments”. *Field Robotics*, 2, pages 1351–1385, 2022.
- Sarlin, Paul-Edouard, et al. "Superglue: Learning feature matching with graph neural networks." *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*. 2020.
- Leroy, V., Y. Cabon and J. Revaud. *Grounding image matching in 3d with mast3r*. in *European Conference on Computer Vision*. 2024.
- A. Phung, G. Billings, A.F. Daniele, M.R. Walter, and R. Camilli, “Enhancing scientific exploration of the deep sea through shared autonomy in remote manipulation”. *Science Robotics*, 8(81) 2023.